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**A Preliminary Interpretation of the 1997 Airborne
ElectroMagnetic (EM) Survey over Fort Huachuca,
Arizona, and the Upper San Pedro River Basin.**

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A Preliminary Interpretation of the 1997 Airborne ElectroMagnetic (EM) Survey over Fort Huachuca, Arizona, and the Upper San Pedro River Basin.

by

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SUMMARY

This report provides a preliminary interpretation of the March 1997 Upper San Pedro River basin airborne geophysical survey. This survey was carried out for the Environmental and Natural Resources Division of the U.S. Army Garrison at Fort Huachuca, Arizona by Geoterrex, Ltd., under the supervision of the U.S. Geological Survey (USGS). This interpretation is based only upon limited data released to the USGS as of early May, 1997, comprising (a) uncalibrated mathematical inversions (so-called "CDTs") of seven flight-lines of the 60-channel airborne electromagnetic (EM) data, (b) a merged aeromagnetic map, (c) a graphic representation of the flight-lines, and (d) 6 grids representing x- and z-components of channels 2, 6, and 10 (that is, early, middle, and late decay times corresponding to shallow, intermediate, and near maximum depths of penetration of the airborne EM system). This interpretation also presents a preliminary map of the shallow aquifer of the Upper San Pedro River drainage, based upon these limited data, along with apparent lithologic transitions and structures gleaned from these data that may or may not constrain the aquifer.

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This study interprets a shallow conductor observed in the airborne geophysical data as the shallow Upper San Pedro River aquifer. Along the front of the Huachuca Mountains a zone of depressed water table apparently caused at least in part by pump draw-down modifies the shape of the shallow aquifer, and in at least two cases this draw-down appears to breach or nearly breach the aquifer, separating the recharge area on the southwest from the rest of the aquifer.

An “intermediate depth conductor” seen in the airborne geophysical data appears to be a clay body observed in drilling and ground geophysical surveys; it appears to underlie the shallow conductor, and in some places may actually block the shallow aquifer between Fort Huachuca and the San Pedro River. A “deep conductor” observed in the airborne geophysical data on the east side of the Fort is probably a narrow vertical fault coinciding with the buried Tombstone Volcanic Caldera margin. It is unclear from these limited data how this structure affects water movement in the aquifer. The data available must still be considered incomplete in both spatial coverage in the north, northeast, and southeast, and in the inversions (the conductivity-vs-depth images) of the March 1997 airborne survey available to the authors.

Isotopic evidence reported elsewhere, and the appearance of the “intermediate conductor”, both suggest that there is at least some natural isolation between the recharge areas west of Fort Huachuca and much of the San Pedro River in the surveyed area. If this is the case, then much if not most of the water in the San Pedro Riparian National Conservation Area must derive from the upper reaches of the San Pedro River drainage in Mexico.

INTRODUCTION

In early March 1997 a 20-channel, 3-axis airborne ElectroMagnetic (“EM”) survey was flown over most of the Fort Huachuca Army base and nearby areas using a proprietary data-acquisition system called “GEOTEM”, developed by Geoterrex, Ltd. of Ottawa, Canada. The object and intent of this survey was to map the shallow aquifer in the Upper San Pedro River drainage, to identify depressions of the water table around existing well-fields, and to determine what, if any, impact these well-fields have on the water flowing in the San Pedro Riparian National Conservation Area established by Congress in 1988. The target surveyed covers a roughly diamond-shaped area stretching between Fort Huachuca and the San Pedro River in Cochise County, southern Arizona (See Figure 1). The approximate limits of the survey are latitudes 31°25'N and 31° 45'N and longitudes 110° 05'W and 110° 25'W (See Figure 2). In Figure 2 the reader will note the remarkable precision of the flight-path acquisition. This excellent coverage is due to the use of a Differential GPS navigation system, referenced against Geoterrex’s GPS beacon located at the Fort Huachuca-Sierra Vista airport in the northwestern part of the surveyed area. The coverage for the main part of the survey used a 1/4 mile spacing and was oriented approximately NE-SW; the northwest and southeast parts of the survey were flown with the same orientation but with 1-mile spacing. Because of the inability to drape-fly the southwestern margins of the survey area using a NE-SW orientation (the part abutting against the Huachuca Mountains) the southwestern part of the survey was flown with 1/4-mile spacing but in a perpendicular orientation along the trend of the mountain front, i.e., in a NW-SE direction. In all, approximately 945 line-miles (1,520 line-km) were flown, including seven NW-SE tie-lines acquired for magnetic data leveling purposes.

GEOLOGIC AND HYDROLOGIC BACKGROUND

A number of hydrology studies of the Upper San Pedro River drainage have been produced over the years, one of the earliest being Brown and others (1966). The most

recent study includes a detailed hydrologic model, developed by the Arizona Department of Water Resources (Corell and others, 1996). Corell and co-authors gathered existing well and gauging station data, and constructed a hydrologic model for the drainage that assumes a fairly simple basin structure. A regional geology and tectonics map was completed by Drewes (1980) that was later supplemented by a 1:50,000-scale geologic map by Moore (1993). This latter map outlines a newly-discovered volcanic center and shows that parts of the Tombstone Caldera underlie the eastern margins of Fort Huachuca, including land covered by the airborne geophysical survey. Together, these reports forced a fundamental reconsideration of the sub-basin structure. Subsequent reports by Gettings and Houser (1995) and Gettings and Gettings (1996) now provide us with an approximate map of the depth to bedrock beneath the post-Cretaceous basin fill of the sedimentary-rock-crystalline-rock contact underlying the Upper San Pedro River drainage. It shows a depression in the bedrock as much as a kilometer deep near Huachuca City, with some of the shallowest crystalline rock less than 800 feet deep underlying parts of Sierra Vista; this latter is confirmed by a well that intersected crystalline basement. This well-log was discovered after the modeling was completed and verified the existence of the predicted bedrock high. A recent seismic reflection study designed to map the water table and the shallow Upper San Pedro aquifer (Environmental Engineering Consultants, 1996) was inconclusive.

AIRBORNE EM SURVEY PARAMETERS

The Upper San Pedro River basin survey was flown 10-15 March 1997 using the proprietary time-domain 20-channel, three-axis GEOTEM airborne electromagnetic surveying system developed and marketed by Geotrex, Ltd., of Ottawa, Canada. The survey aircraft was a Brazilian CASA Turboprop with transmitter loops capable of 600 amperes wound around the aircraft in a horizontal plane (vertical axis) from nose-boom to wing, to tail to wing to nose-boom. Two detector “birds” were towed, one a magnetic sensor flown at about 40 meters (130 feet) behind and below the survey aircraft and the

other was a 3-coil (x, y, and z) system flown about 60 meters (200 feet) below the survey aircraft. This latter towed bird is capable of measuring the secondary transient electromagnetic responses in x-axis (along-flight-line), y-axis (side-looking), and z-axis (vertical) orientations. Because of the nature of an alternating-current electromagnetic dipole, the signal coupling of this transmitter configuration with the subsurface induces eddy currents in the ground that have components in all three orientations.

The x-axis (in-line) and y-axis (side-looking) receiver components are optimally coupled for detecting vertical conductors (perpendicular and parallel to the flight-path respectively), such as water-filled faults or massive sulfide deposits. The z-axis (vertical-axis co-planar) component signal is optimally coupled for measuring the conductivity of layers beneath the ground surface. All three components will report anomalies over powerlines, pipelines, and grounded fences. The transmitter is geometrically configured by design to induce (primarily) horizontal-plane eddy currents in the ground, and the vertical (co-planar) receiver coils can detect a secondary field from these eddy currents as deep as 400 meters in some cases.

The GEOTEM transmitted waveform is a unique half-sine-wave that can be lengthened for maximum depth of penetration or shortened for maximum near-surface resolution. For the purposes of this survey the waveform was lengthened to near its maximum for the deepest possible penetration: a 30 Hz repeat-rate and a 4 ms sampling rate were used. The output “channels” consist of sampling windows (see Figure 3) taken at increasing time gates (one can translate this as increasing depth below the surface) along the received secondary waveform for each of three coil orientations. In addition to 60 EM channels (20 time-windows each, times the three orientations) the GEOTEM system also acquires data from the magnetic sensor and an additional 60-Hz monitoring channel to help identify man-made, grounded metallic structures and separate powerline anomalies from geologic anomalies. These signals are location-corrected during post-flight data-

processing for the distance-lag caused by the retarded position of the two detector birds on their respective cables behind the aircraft.

The GEOTEM system also acquires Differential Global Positioning System (DGPS) location signals as well as continuous videotape of the ground to resolve any remaining man-made-vs-geologic issues, and as backup to the DGPS location information. The EM channels are calibrated periodically by flying over a well-characterized homogeneous target such as seawater, and also calibrated daily by flying the aircraft at the beginning and end of each survey at approximately 8,000 feet AGL (about 2,500 meters above the earth) where ground contribution is negligible, and correcting for residual signal caused by interaction of the transmitted signal with the body of the aircraft. Barometric elevation and radar-altimetry channels are also acquired to verify the vertical position of the aircraft. Since the transmitted signal from an alternating electromagnetic dipole such as the GEOTEM transmitter antenna falls off as one over the distance cubed, it is critically important to maintain the aircraft as close as possible to the ground for maximum penetration of signal. During the San Pedro River basin survey the aircraft was “drape-flown” over the terrain at 400 feet AGL (about 125 meters above the ground surface), with the distance raised to 500 feet (nominally 154 meters) over the populated areas such as the City of Sierra Vista and Fort Huachuca in order to conform to FAA regulations. While flying at 400 feet AGL the magnetometer is nominally 120 feet (about 40 meters) below the aircraft and the EM bird is about 160 feet (more than 50 meters) below the aircraft.

SURVEY DATA RELEASED TO USGS AND A PRELIMINARY INTERPRETATION

Figure 4 shows the magnetic data collected by the GEOTEM system during the March 1997 survey. For reasons that are not clear, the preliminary data released to the USGS

did not include either magnetic or EM data for flight-lines 156-159 in the southeastern quadrant of the surveyed area.

The magnetic data show what may be high magnetic volcanic or intrusive rocks in the bedrock beneath the northeastern half of the surveyed area. On the southwestern edge magnetic rocks from the Huachuca Mountains can be just barely seen in these data. An Euler deconvolution depth-to-source (not shown here; awaiting the complete magnetic data) shows some of the deepest basement to be in the northwest of the surveyed area, in agreement with Gettings and Houser (1995) and Gettings and Gettings (1996).

Figures 5 through 10 are gridded data-files released to the USGS from Geoterrex. These represent the airborne EM response of channels 2, 6, and 10, with an x-component (emphasizing vertical structures perpendicular to the flight-path) and a z-component (emphasizing conductive layers beneath the aircraft) for each channel. Figures 5 and 6 are very similar, representing the x- and z-components of EM channel 2. Both show lithologic transitions in the central and northeastern parts of the surveyed area, and conductors on the southwestern edge where Fort Huachuca and the Huachuca Mountains are located. In the central area there are numerous high-frequency anomalies that are caused by grounded man-made structures, i.e., powerlines, pipelines, grounded fences, etc. The amplitude scale of figures 5 - 10 are in parts per million according to one note found in the Geoterrex "read.me" file accompanying the grids, and as picoVolts per square meter in another part of the "read.me" file. This difference is not important since the two are related by a simple constant derived from calibration runs. Interpretive results from these and subsequent EM figures are shown following this discussion. The final report from Geoterrex should show the calibrated EM channels of the secondary field in parts per million of the primary field.

Figures 7 and 8 show the x- and z-components of EM channel 6. They are also highly correlated to each other and also similar to Figures 5 and 6. The x-component signal has

substantial “herringbone”, the jagged location noise along the flight-lines. These are caused by the relatively greater sensitivity of the x-component signal to small vertical fluctuations in the aircraft’s flight path. On both these figures the cultural artifacts (including the narrow linear and sublinear anomalies) are relatively stronger than on Figures 5 and 6. This is due to the fact that the returned signal from these “deeper” channels has a lower amplitude and thus a greater automatic gain is applied during acquisition. Because of this greater gain, the cultural artifacts make up a relatively larger component of the dynamic range of the amplifiers than on the earlier (“shallower”) channels. The north-south linear anomaly showing up on these figures in the eastern side of the surveyed area coincides with a principle road (and accompanying powerline and/or pipeline) here. Highway 90 now also shows up clearly in the data. The lithologic boundaries on the northeastern side have not changed substantially from Figures 5 and 6.

Figures 9 and 10 are also relatively similar to each other and to Figures 5 through 8. These two new figures show the x- and z-components of EM channel 10. The increased gain and therefore even smaller contribution of the geology to the total dynamic range of the composite signal in these channels has caused the cultural artifacts to now dominate the figures. Again, for geometric reasons the x-component signal shows more “herringbone” than the z-component. The conductive contribution of the front range of the Huachuca Mountains is substantially diminished in these figures, but a lithologic boundary along the Nicksville fault can still be clearly seen. In these figures, it is now relatively easy to draw an outline of the human presence (the man-made electromagnetic interference) if that was our objective. In fact, this man-made EM interference makes it difficult (but not impossible) to reduce the EM channel data through mathematical inversion to conductivity-vs-depth cross-sections (CDTs discussed in detail below).

Figure 11 serves to reference selected flight-lines with the geologic map of Drewes (1980). Water wells are shown as circles on this figure, and the accompanying numbers are depth-to-water table as of 1997 (Gretchen Kent, U.S. Army NEPA Coordinator, Fort

Huachuca Garrison, written communication, 1997). The fine red lines are the traces of selected (CDT) flight-lines superimposed on the geologic map, and the heavy dot-dashed red line emphasizes the San Pedro River for clarity.

Figure 12 shows lithologic boundaries and faults interpreted from the EM data of Figures 5 - 10. The lithologic boundaries in the northeastern parts of the surveyed area appear to mark the contact, hidden beneath Holocene to Miocene floodplain deposits, of the Upper Cretaceous Tombstone Volcanic Center's volcanic flows and quartz monzonite bodies found outcropping farther to the northeast. It is worth noting that the Sawmill Canyon fault is closely matched in the EM data by an offset in lithologic boundaries along most of its length. The EM data suggests a horizontal throw along this fault of as much as 4 kilometers (about 2.5 miles). The inferred Nicksville fault on the Drewes (1980) map (found at the Huachuca Mountain front in the southwestern part of the figure) is also represented by a lithologic boundary offset in the EM data, but the mapped fault is displaced to the northeast by at least 500 meters from the boundary seen in the EM data.

Figures 13 through 19 represent seven different CDT (Conductivity Depth Transform) profiles, that is, mathematical inversions using all 20 channels of the z-component of the EM signal to generate conductivity-vs-depth cross-sections along the flight profiles. These CDT's are preliminary products, released to the authors informally by the Geoterrex party chief on-site at the conclusion of the airborne EM survey. The lines were chosen to provide a representative series of cross-sections of the top 200-400 meters (up to 1,200 feet deep) of the Upper San Pedro River drainage. In addition, several lines were selected to cross known wells and basement topographic features derived from gravity and magnetic data (Gettings and Houser, 1995; Gettings and Gettings, 1996). It should be noted that these CDT's are vertically uncalibrated, and the horizontal scales also vary from line to line. Nevertheless, when re-scaled they appear to show conductive bodies as deep as 400 meters beneath the surface along the profiles. This is generally when there is

sufficient signal and relatively little man-made electromagnetic interference. The CDT's will be each briefly discussed, starting on the northwest and ending on the southeast.

For purposes of the following discussion it is useful to remember that in most cases clay bodies at depth are generally wet and show up as relatively conductive features in CDTs. The same holds for most aquifers in the southwestern U.S., where relatively little recharge and substantial evapotranspiration leaves significant ion-content in the water (30 ohm-meters is typical). While one conductor may be an aquitard and the other an aquifer, they will *both* appear as conductors in CDTs. A shallow aquifer typically manifests itself as a flat or subhorizontal conductive layer. Because the system parameters were chosen to maximize depth penetration for this survey, the horizontal conducting layer believed to represent the shallow San Pedro aquifer is generally quite well resolved (and its upper limit agrees well with known water-table levels). A water-filled (normal) fault zone will also show up as a conductor (red and purple colors on the CDTs), but it will generally be narrow, vertical or subvertical, and will pass through most of the cross-section. When there is grounded man-made structural interference (usually in the form of powerlines, pipelines, or grounded metallic structures such as a metal fence) we find that these anthropogenic conductors tend to dominate the dynamic range of the airborne EM system, typically drowning out the weaker signal from the longer-time channels that represent greater depths below the surface. For this reason, the CDTs show numerous zones of white color rising from the bottom of the cross-section where the inversion program cannot resolve the deeper conductors, and their contribution falls below the noise threshold as the automatic gains are suppressed to accommodate the superficial man-made conductors. With these general guidelines, we now proceed with an analysis of the CDTs.

Figure 13 is the CDT from flight-line 103 in the northwestern edge of the surveyed area (see Figure 11). Two shallow, subhorizontal conductive bodies can be seen on this figure, probably representing the shallow Upper San Pedro River basin aquifer since their

upper limits in subsequent profiles agree well with water-table depths where known. Left of center is a depression in the water table almost certainly due to draw-down by pumping. This cone of depression appears to have nearly breached the aquifer at its lowest point. There is a vertical conductive anomaly on the right-hand side of the figure that is probably a water-filled fault zone. It appears to extend from the aquifer to the maximum depth that the inversion process can resolve (probably close to but less than 400 meters or 1,200 feet below ground surface). This vertical conductor aligns precisely with the mapped western boundary of the buried Tombstone Caldera (Moore, 1993). At several places along the horizontal length of this CDT the inversion process fails (this is represented by white coming up from below). This failure to resolve the deeper layers is caused by interference from grounded man-made structures, which contribute enough electromagnetic noise to swamp the progressively weaker signal from the deeper layers.

Figure 14 is the CDT from flight-line 112. It appears to show a continuous aquifer across its entire length, but the depression of the water table west of Highway 92 is deeper than on line 103 and yet still appears to be continuous, that is, there is probably hydraulic connectivity from west to east. Again, there is substantial man-caused EM interference beneath the central and eastern parts of the profile, and a possible vertical offset (west side down-thrown) in the middle. This possible offset, it should be noted, may be an artifact in the data caused by EM interference with the inversion algorithm. On the west side of the profile, the irregular shape of the sub-horizontal conductor (the probable aquifer) may be related to block-faulting at the front-range of the Huachuca Mountains. On the east side the vertical conductor (possible fault-zone) still is visible, but there appears to be a thick, horizontal conductive body below the aquifer. This “intermediate conductor” may or may not represent a clay body observed in drilling and vertical electrical geophysical surveys reported to the authors (Don Pool, USGS Water Resources Division, Tucson, AZ, written communication, 1997). If so, this intermediate body (apparently related to the Tombstone Caldera) appears to lie *beneath* the shallow conductor (the presumed shallow aquifer) and may therefor not serve as a barrier between

it and the San Pedro River at this point. A possible alternative interpretation of this intermediate conductor is a deeper aquifer lying below the shallow aquifer. If this is the case, the shallow conductor may correspond to the upper unit of basin fill and the intermediate conductor would then correspond to the lower unit of basin fill of Brown and others (1966).

Figure 15 is the CDT from flight-line 124. This line passes close to several wells (see Figure 11) and the decreasing depth to water table in these wells as one moves east is clearly seen in the subhorizontal shallow conductor (the presumed shallow aquifer), which can be seen getting demonstrably shallower to the east. Man-made EM interference makes it difficult to resolve the western margins of the profile (this part lies over the western end of the residential and office part of Fort Huachuca) but the depression of the water table is still clearly there, and hydraulic connectivity appears to still be intact, with a substantial volume of conductive material (deeper water-filled sediments?) underlying the water-table depression at depth. On the eastern side of the depression in the water table is a pronounced shoulder that appears to be from substantial surface recharge. This may be from waste storage ponds on Fort Huachuca where according to calculations (Gretchen Kent, U.S. Army NEPA Coordinator, Fort Huachuca Garrison, oral communication, 1997) there is 500-acre-feet/year water-loss that can't be explained by evapotranspiration. On the eastern side of the profile the apparent clay body remains visible at depth beneath the shallow aquifer.

Figure 16 is the CDT from flight-line 137; this is the first CDT that touches or crosses the San Pedro River (on the eastern end of the CDT). This complex profile shows several draw-down zones in the shallow presumed aquifer seen on CDTs to the north (Figures 13 - 15). The deepest depression in the water table is on the western end of the profile which unfortunately cannot be resolved completely. This profile doesn't extend to the Huachuca Mountains because the aircraft was forced to terminate the line to avoid the mountains. There may also be recharge in at least three points (both recharge and draw-

down may be from locations off-line, and we may only be seeing “side-swipe” in this profile; further adjacent CDTs should be calculated and compared to resolve this question). An alternative explanation for the vertical irregularities on the western end of this profile could be that we are seeing manifestations of the block-faulting beneath the sediments east of the Huachuca Mountains. As in the previous CDTs, the impact of human cultural interference is substantial, making it difficult for the inversion program to resolve deeper structures. Despite this interference, there is at least one and probably two vertical conductors that almost certainly are water-filled fault-zones just to the left of the center of the profile. The “intermediate conductor” (interpreted to be the clay body reported by Pool) observed on profiles to the north appears now to have clear western limits but a pronounced western dip of the interface on this profile.

There are offsets on the eastern side of flight-line 137 that appear due to normal faulting or steep contacts among the volcanic rocks exposed there. There is some uncertainty in the registration of this end of the profile to points on the ground, because the party chief apparently edited the lines used to construct Figure 2 to make its margins even. It is likely that the shallower isolated conductor represents the San Pedro River and its underflow; if so, it suggests that there is a down-thrown block (normal or block faulting) in the volcanic rocks immediately to the east, with an extension of the aquifer, probably with hydraulic connectivity, across the fault and into the Tombstone Hills area farther east. The isolated character of the apparent San Pedro River conductor here also suggests another fault to the west; there is a normal fault implied but not explicit in the Drewes (1980) cross-section D-D’ a short distance to the north, and in fact it is almost certainly controlled by the Tombstone Caldera margin. An alternative explanation for this apparent break in the shallow (“river”) conductor is that the deeper conductor observed on CDTs to the north (the clay body observed in drilling and electrical geophysical soundings by Don Pool, written communication, 1997) now appears in flight-line 137 to be dipping to the west, becoming notably shallower on its eastern end, where it may in fact be shallow enough to break or bound the shallow aquifer and separate it from the San

Pedro River and its underflow. The correct explanation may be a combination of these two alternatives, and must await further processing of additional adjacent CDTs, and possibly even ground-based time-domain EM soundings to resolve. At this point beneath the flight-line there appears to be very little hydraulic connectivity across this apparent natural boundary.

Figure 17 is the CDT from flight-line 142. Like line 137, the western depression in the water table along the front-range of the Huachuca Mountains is not completely resolved because of the southwestern limit of the flight-line; this may not even be a true cone-of-depression but instead may simply represent the appearance of block-faulted Huachuca Mountain rocks having lower porosity than the sediments to the northeast. There is substantial man-made EM interference (caused by pipelines, powerlines, grounded fences, etc.) In the western and central parts of this profile, again limiting the resolving power of the CDT inversion process for greater depths. Nevertheless, there appears to be hydraulic connectivity across the main depression in the water table, and possibly one point of recharge (where the shallow conductor believed to be the San Pedro aquifer goes all the way to the surface on the profile). On the eastern side of the profile the “intermediate conductor” (the probable clay body) appears to still have a slight western dip, but generally it distinctly underlies the shallow conductor until its eastern edge, where it may break the hydraulic connectivity of the aquifer. On the extreme eastern edge of the profile, there is a lithologic boundary that may be a normal fault (east-side down-thrown) or possibly a lithologic contact. This boundary coincides with the surface expression of volcanic rocks in the Tombstone Hills.

Figure 18 is the CDT from flight-line 155. Grounded-structure interference is substantial on this profile, but the main depression in the water table on the western side is still clearly delineated. By now it is apparent that this is not strictly a well-field cone-of-depression but might more reasonably be called a “valley-of-depression” since it appears to extend from this profile all the way to the northwest to at least flight-line 103 (Figure

13). There may be a break in hydraulic connectivity on its eastern side, where pump draw-down (or some other cause) may have breached the aquifer. There is complex structure apparent on the western end of the profile, but it is difficult to interpret. Without close-by neighboring CDT profiles to compare, it is unclear if this is caused by man-caused EM interference or represents slump-blocks of the Huachuca Mountain margin. In the central part of the profile there is some suggestion of the existence of a deeper aquifer, but again grounded-structure interference makes this difficult to resolve. There are several places along the central part of the profile where the shallow aquifer appears irregular; this could be an artifact of the grounded-structure interference or may be evidence of draw-down by small, isolated local wells. At one point in the center there is a surface conductor apparently caused by an underground aqueduct. The “intermediate conductor” is well-resolved and appears to be unconnected to the shallow aquifer overlying it. It is narrower to the south in the CDTs. On the eastern margin of the profile there is a small depression in the water table approximately coincident with the west side of the San Pedro River; the River itself and its apparently substantial underflow appear to be well-resolved just to the east of this depressed zone.

Figure 19 is the final CDT from flight-line 158. Grounded structure interference almost totally dominates the western half of the profile; nevertheless it appears that the depression of the water table observed in the northern profiles has not extended this far southeast. It is impossible to say anything about the hydraulic connectivity. In the central part of the profile, the “intermediate conductor” is clearly resolved, but is somewhat narrower. There is a clear offset, almost certainly a right-side-down-thrown normal fault, that appears to exactly coincide with the San Pedro River on this profile. This offset may indicate that much if not most of the San Pedro River in the surveyed area is fault-controlled, or otherwise constrained by structural features related to the Tombstone Caldera. In the north (e.g., flight-line 103) the deep conductor acts like a vertical water-filled fault zone, while on this southeastern-most profile (flight-line 158), it appears that the fault is probably no longer water-filled, but instead offsets the subsurface

conductors, one of which may be a deeper aquifer but is probably an extension of the “intermediate conductor” (interpreted as the clay body of Pool). This lower, down-thrown body may or may not be a southern extension of the sharp vertical conductor seen on most of the northern profiles; it is clearly a discrete conductive body which now appears to no longer be connected to the San Pedro River or its underflow. Again, closer-spaced additional CDTs will be required to interpret this feature with more confidence.

CONCLUSION AND SUMMARY INTERPRETATION

Figure 20 is a plan-view summary representation of the interpretation of the seven CDT profiles discussed above. It shows the shallow conductor we interpret as the shallow Upper San Pedro aquifer as a semi-transparent blue field overlaid on the geology map of Drewes (1980). It appears to extend both northwest and southeast beyond the bounds of the surveyed area. The aquifer’s extent on the north and east is not clear because we lack survey coverage there also. Along the front of the Huachuca Mountains a zone of depressed water table apparently caused at least in part by pump draw-down modifies the shape of the shallow aquifer, and in at least two cases (flight lines 103 and 155) this draw-down appears to breach or nearly breach the aquifer, separating the recharge area on the southwest from the rest of the aquifer. In other parts there appears to be hydraulic connectivity between the two sides of the “valley-of-depression”, and in at least one place (flight-line 124, Figure 15) there appears to be substantial water-filled sediments *beneath* the “valley-of-depression”.

The “intermediate conductor” is represented by a semi-transparent brown field overlaying the geology map. We infer this to be the clay body reported by Pool, and it appears to underlie the shallow conductor, but on lines 137 and 142 may reach up and actually block the shallow aquifer between Fort Huachuca and the San Pedro River. We can speculate that this clay body may be lake-sediments that developed against the Tombstone Caldera margin shortly after its formation, or may be zeolite-rich outflow volcanoclastic bodies

stemming from the original eruption. The deep conductor on the east appearing as a narrow vertical fault on the eastern margin of line 103 (exactly coinciding with the mapped Caldera margin in Moore, 1993) appears to be continuous over most of the eastern part of the surveyed area, becoming a normal fault (right-side down-thrown) beneath the San Pedro River on the southeastern margin of the map. At this point it no longer agrees exactly with the inferred Caldera margin on Moore's (1993) map. The southern end of the surveyed area appears to be dominated by grounded-structure interference, making it difficult to resolve structure and the shallow aquifer in this area.

Figure 21 combines well and water-table information with the interpretation from the EM channel map and the interpretation of the CDTs, and overlays all of this over the geology map of Drewes (1980) as a reference. It must be stated again that these interpretations are preliminary, based on incomplete information received so far from the airborne EM survey. In several cases, alternative interpretations of individual features are given, but these should not be perceived as exclusive of other possibilities. Additional CDTs using the existing data are necessary to resolve continuity (and even in some cases the identity) of many of the features, and additional airborne coverage would be extremely helpful in mapping the aquifer north and south of the rather narrow zone covered by this survey.

This 1997 airborne EM survey provides a major new source of information about the Upper San Pedro River aquifer. While not yet completely resolved using the limited data available to the authors, the relationship between the Upper San Pedro aquifer and the San Pedro River is now clearer than it has been in the past. Isotopic evidence (Pool, oral communication, 1997) and the appearance of the "intermediate conductor" (believed to be a clay body) both suggest that there is at least some natural isolation between the recharge areas west of Fort Huachuca and much of the San Pedro River in the surveyed area. If this is the case, then much if not most of the water in the San Pedro Riparian area must derive from the upper reaches of the San Pedro River drainage in Mexico. There appears to also be some recharge of the Upper San Pedro River aquifer in and around Fort

Huachuca and Sierra Vista (possibly from waste ponds), recharge apparently not included in the hydraulic modeling of Corell and others (1996).

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The airborne EM survey was supported by Gretchen Kent, the U.S. Army NEPA Coordinator of the Fort Huachuca Army Garrison, who gave up much of her time and boundless energy during the weeks prior to and during the survey to ensure its success. The survey could not have been carried out in an area of such intense and diverse activity as Fort Huachuca without the willing can-do attitude of numerous flight controllers and range-managers, who bent plans and activities as necessary to avoid interference with the survey. We were supported fully by public-affairs officers and local newspapers, who kept the local population informed about why the strange-sounding CASA aircraft was overflying their base and town. Representatives of the Drug Enforcement Agency kindly lowered the tethered surveillance dirigible (the "Aerostat") so the Geoterrex aircraft could complete the survey in the shortest time possible. In Denver, Pat Hill provided the contract management that ensured a professional and complete survey, and Vic Labson and Maria Desczc-Pan provided suggestions on survey parameters that eventually led to a successful survey.

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FIGURES

Figure 1. Index map showing the location of the GEOTEM airborne electromagnetic survey over Fort Huachuca and Sierra Vista, southeastern Arizona.

Figure 2. Flight-lines completed during the GEOTEM survey.

Figure 3. Survey parameters and time-gates in the GEOTEM transmitter waveform.

Figure 4. Magnetic anomaly map obtained as part of the GEOTEM survey, Fort Huachuca, Arizona. (one version with and one without contour lines).

Figure 5. Map showing the EM response (relative conductivity) for GEOTEM channel 2 with the receiver coil oriented along the flight path. Scale 1:300,000.

Figure 6. Map showing the EM response (relative conductivity) for GEOTEM channel 2 with the receiver coil oriented vertical-coplanar with the transmitter. Scale 1:300,000.

Figure 7. Map showing the EM response (relative conductivity) for GEOTEM channel 6 with the receiver coil oriented along the flight path. Scale 1:300,000.

Figure 8. Map showing the EM response (relative conductivity) for GEOTEM channel 6 with the receiver coil oriented vertical-coplanar with the transmitter. Scale 1:300,000.

Figure 9. Map showing the EM response (relative conductivity) for GEOTEM channel 10 with the receiver coil oriented along the flight path. Scale 1:300,000.

Figure 10. Map showing the EM response (relative conductivity) for GEOTEM channel 10 with the receiver coil oriented vertical-coplanar with the transmitter. Scale 1:300,000.

Figure 11. Map showing CDT-selected flight-lines superimposed on the geology map of Drewes (1980), along with the San Pedro River and wells with depth to water-table recorded in 1997. Scale 1:195,000 to maximize resolution in the figure.

Figure 12. Map showing interpretations of faults and buried lithologic boundaries derived from the GEOTEM channel maps of figures 5 - 10. Scale 1:195,000.

Figure 13. CDT (conductivity-vs-depth) profile for flight-line 103. Variable horizontal scale, vertical scale to 400 meters. The conductivity scale ranges from purple and red for high conductivity to blue for low conductivity.

Figure 14. CDT profile for flight-line 112. Scales the same as Figure 13.

Figure 15. CDT profile for flight-line 124. Scales the same as Figure 13.

Figure 16. CDT profile for flight-line 137, showing an uncalibrated Log_{10} conductivity scale. Scales the same as Figure 13.

Figure 17. CDT profile for flight-line 142. Scales the same as Figure 13.

Figure 18. CDT profile for flight-line 155. Scales the same as Figure 13.

Figure 19. CDT profile for flight-line 158. Scales the same as Figure 13.

Figure 20. Map showing interpretations of the shallow conductor (apparently the shallow Upper San Pedro River aquifer), zones of depression of the water table, apparent hydraulic connectivity, the location of the “intermediate conductor” (probably a clay body), and the eastern deep conductor (apparently a vertical fault marking the Tombstone Caldera margin buried beneath the sediment), superimposed on the geology map of Drewes (1980). Scale 1:195,000 to maximize resolution in the figure.

Figure 21. Summary interpretive map combining all the above information and interpretations into a single plate superimposed on the geology map of Drewes (1980). Scales 1:125,000 and 1:195,000.

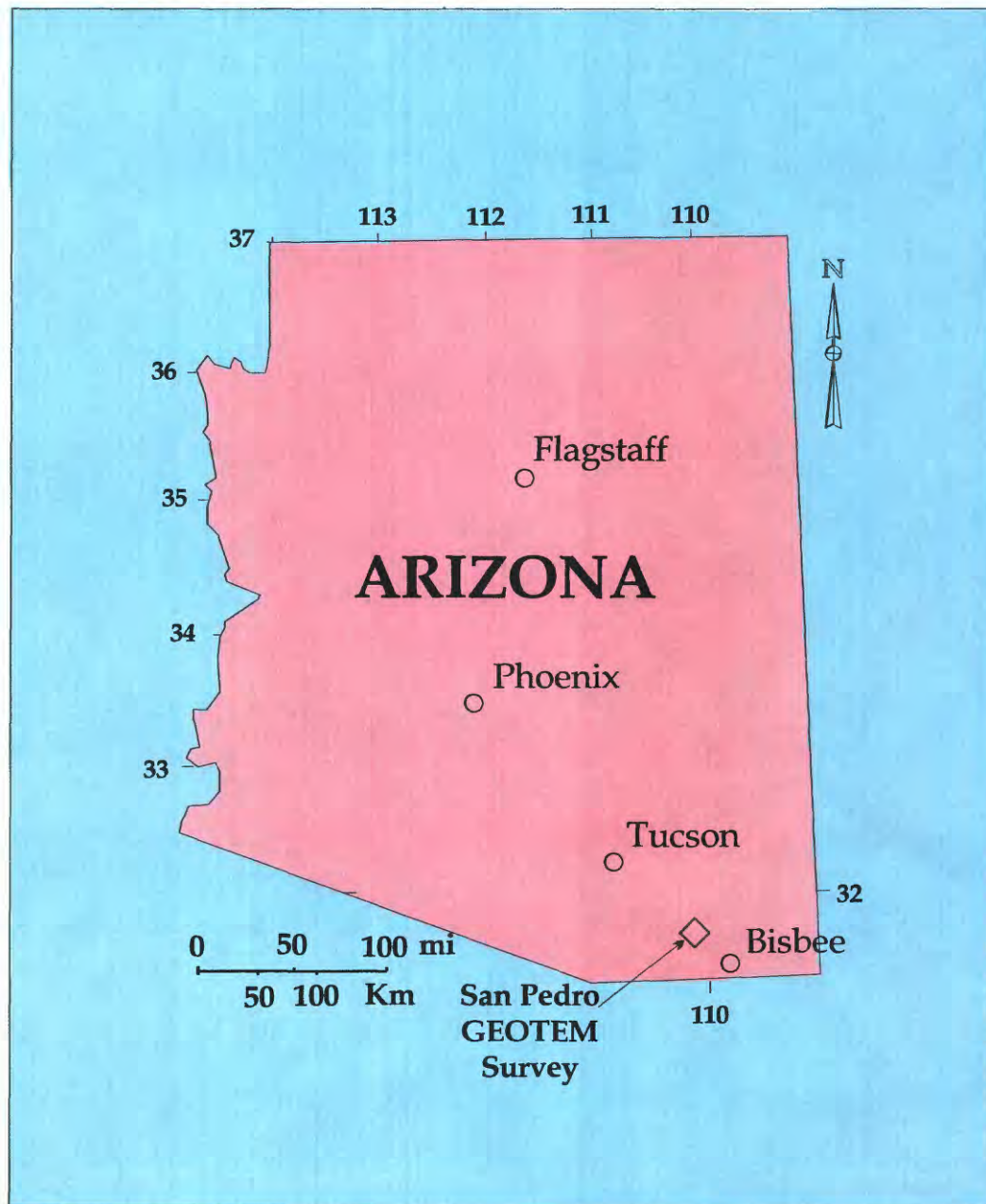


FIG. 1

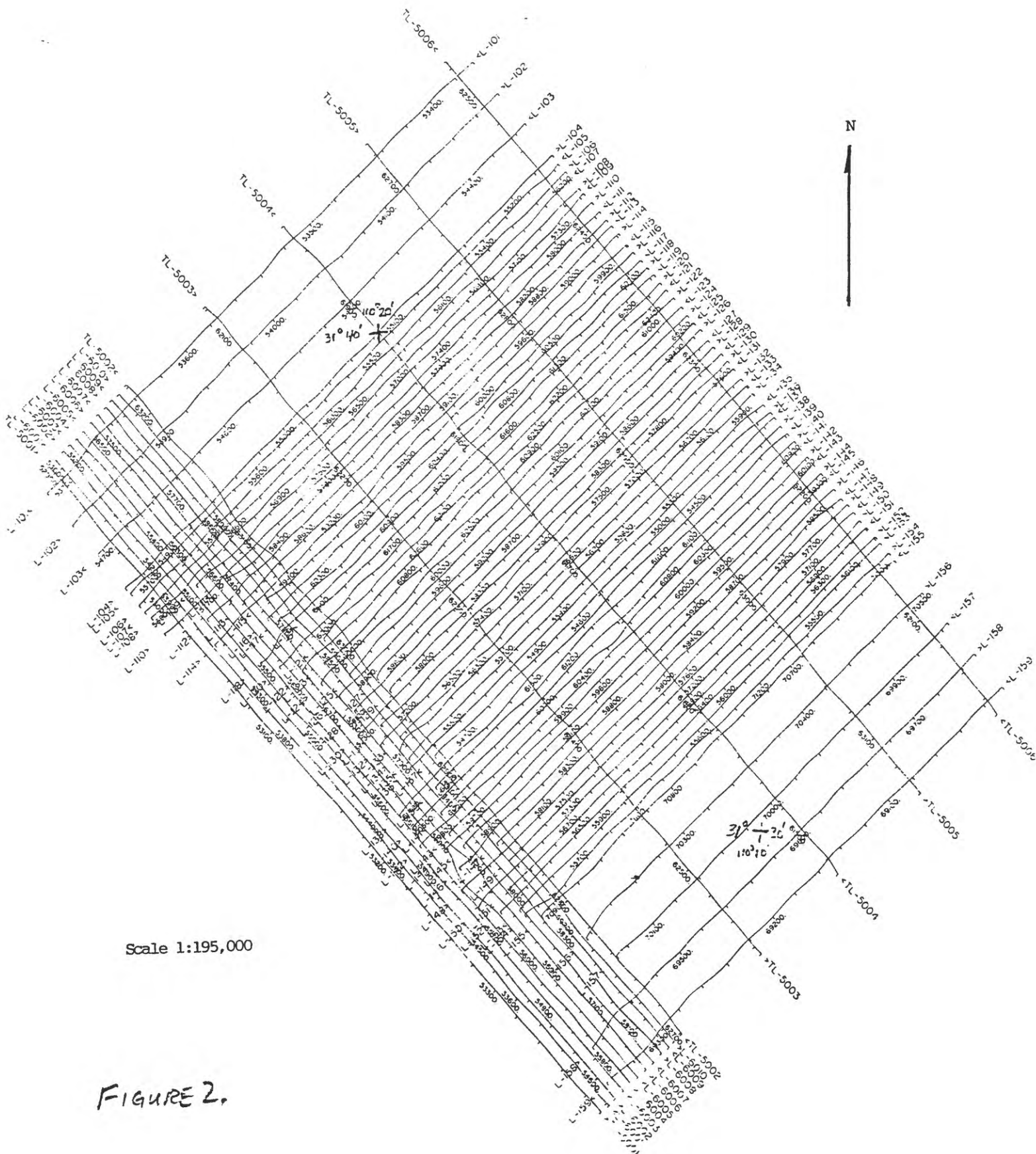


FIGURE 3.

GEOTEM configuration at 30 Hz/4ms operation

FREQUENCY : 30 Hz

COMPLETE CYCLE : 16,667 μ s.

PULSE WIDTH : 4036 μ s.

DELAY TIME : 130 μ s

OFF-TIME : 12,501 μ s

POINT VALUE : 130 μ s.

CHANNEL	GATE POSITION	MID VALUE	WIDTH	CHANNEL	GATE POSITION	MID VALUE	WIDTH
20	2-3	-3841	260	3	45-47	1822	391
19	4-13	-3059	1302	4	48-51	2278	521
18	14-23	-1757	1302	5	52-56	2864	651
17	24-33	-455	1302	6	57-62	3580	781
16	34-34	260	130	7	63-69	4427	911
15	35-35	390	130	8	70-77	5403	1042
14	36-37	586	260	9	78-86	6510	1172
13	38-39	846	260	10	87-98	7877	1562
1	40-41	1106	260	11	99-112	9569	1823
2	42-44	1432	391	12	113-128	11523	2083

- Gate positions are in "points" along the waveform
- Mid-values are in microseconds from the end of the pulse
- Widths are in microseconds.

GATE POSITIONS

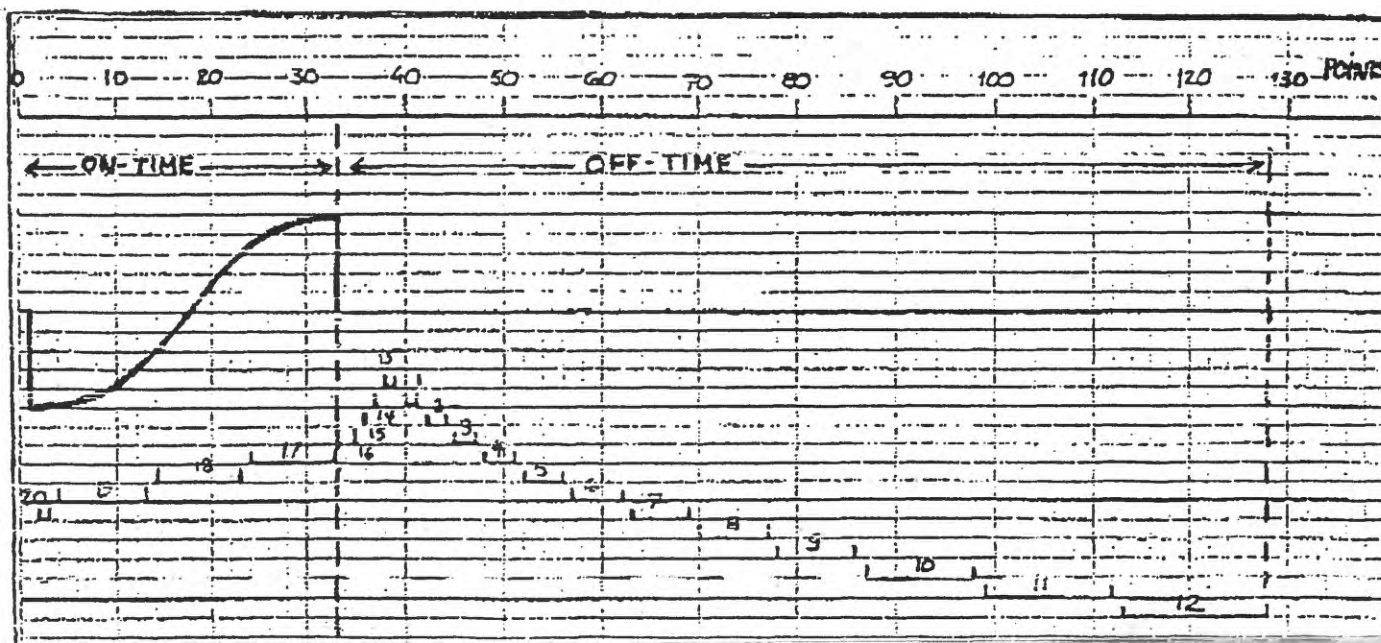


FIGURE 4.

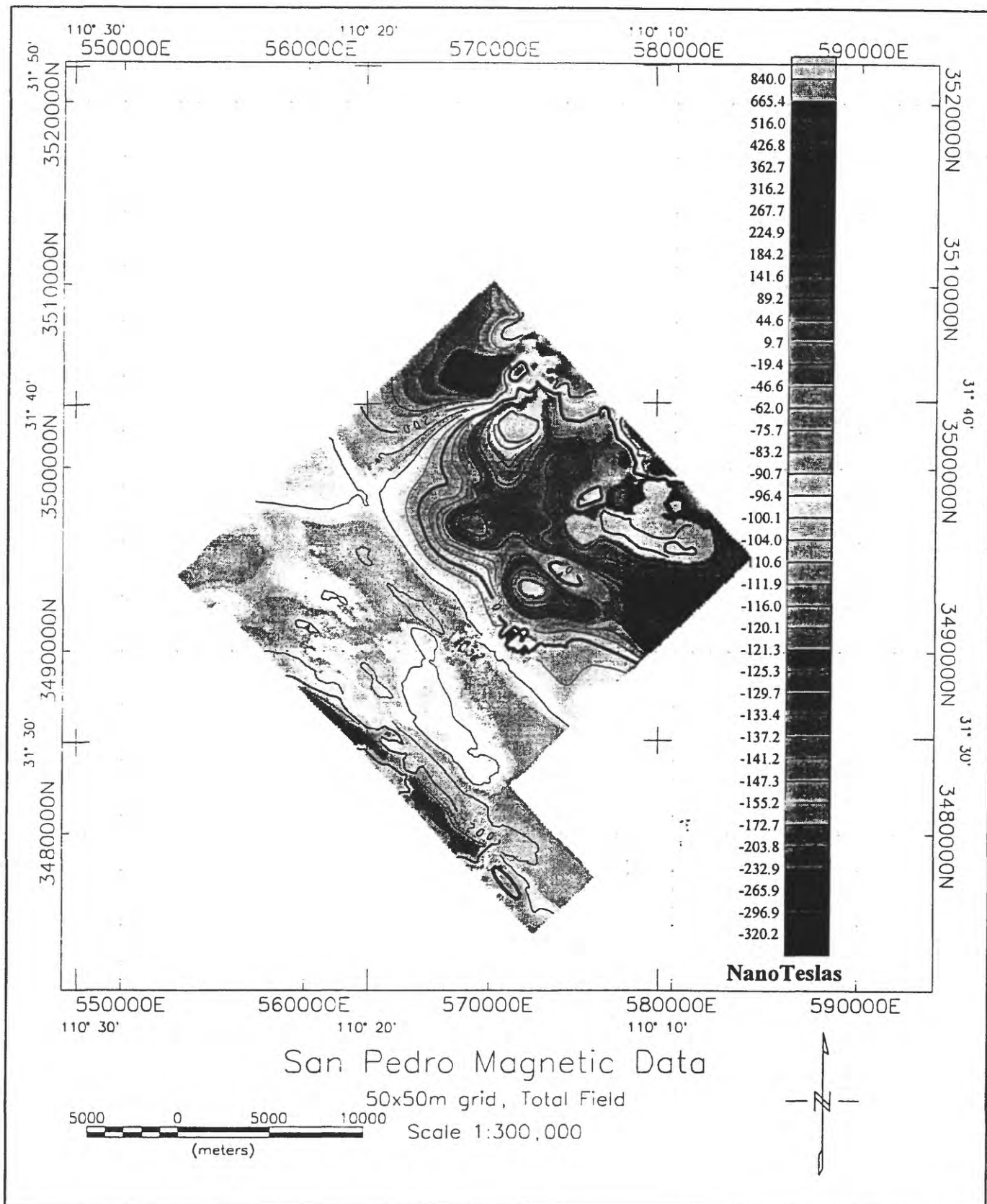


FIGURE 5.

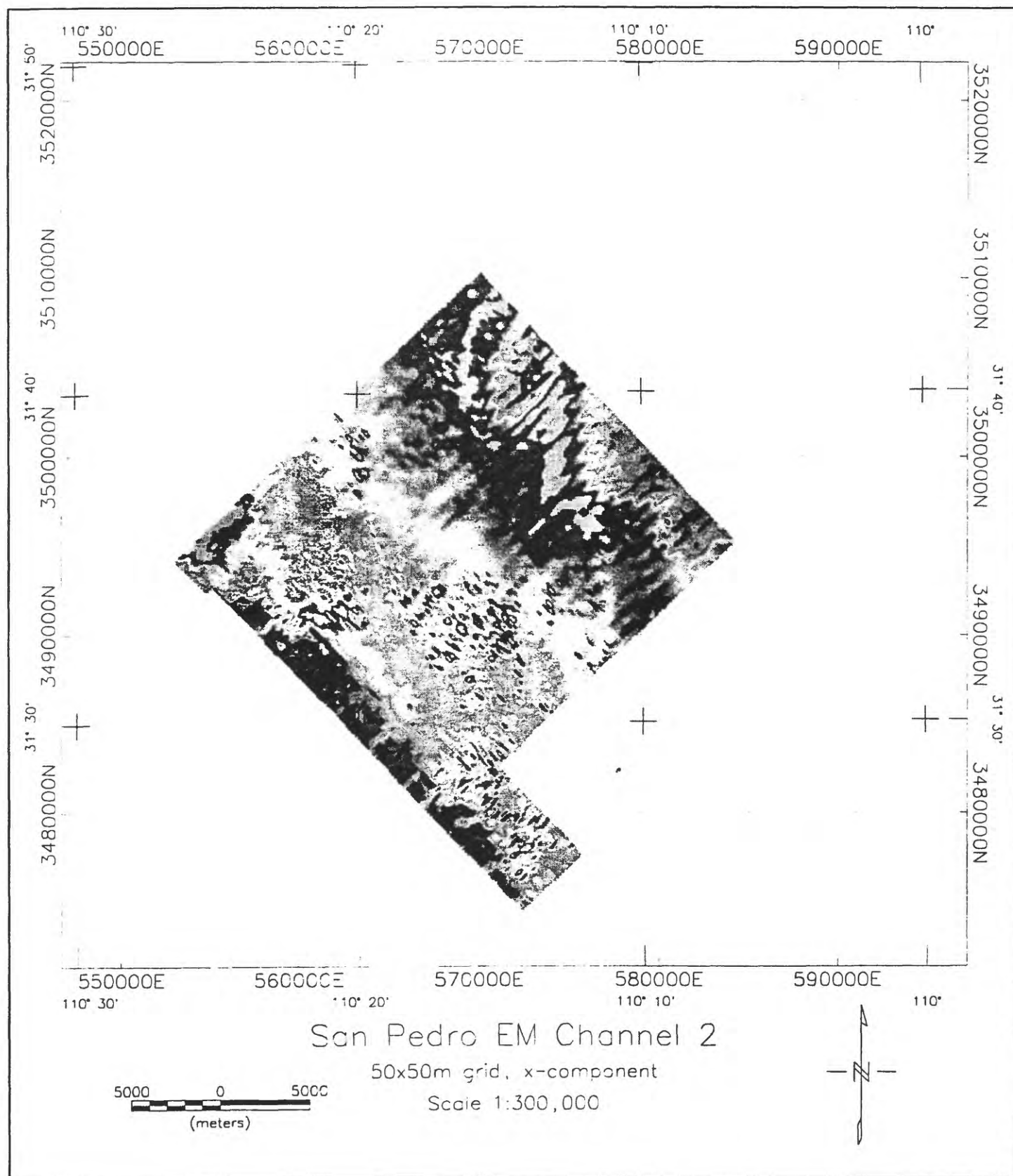


FIGURE 6.

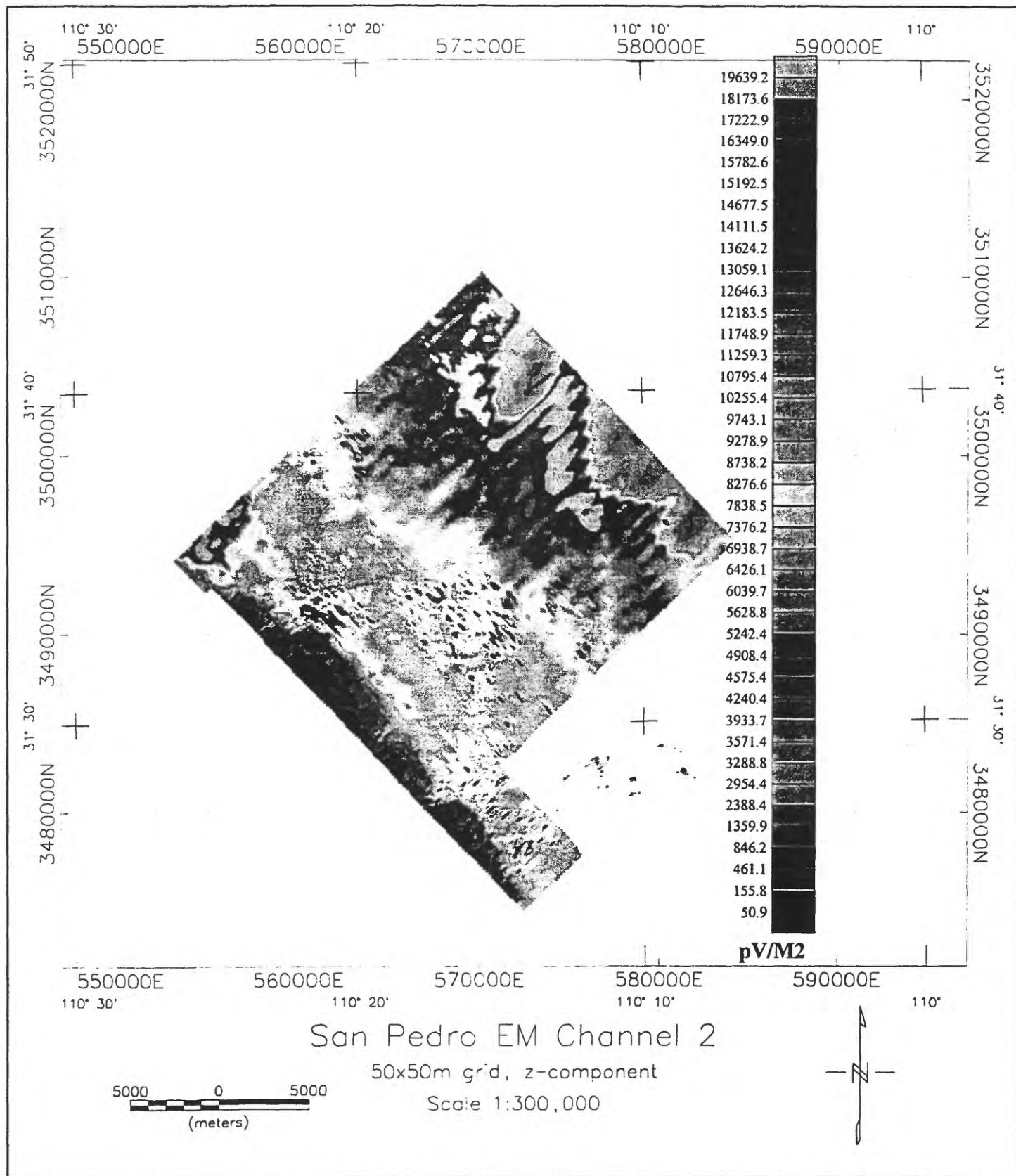


FIGURE 7.

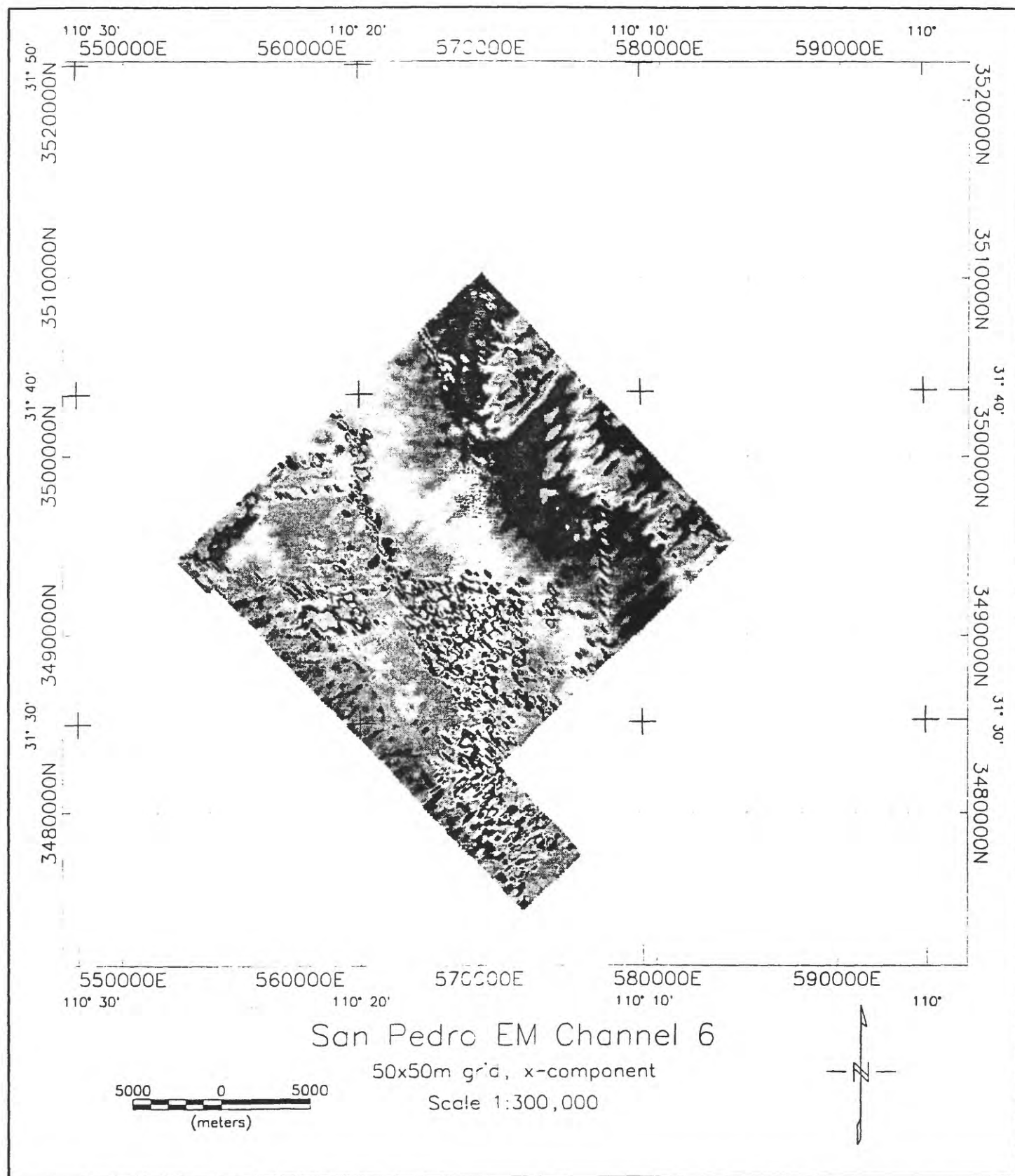


FIGURE 8.

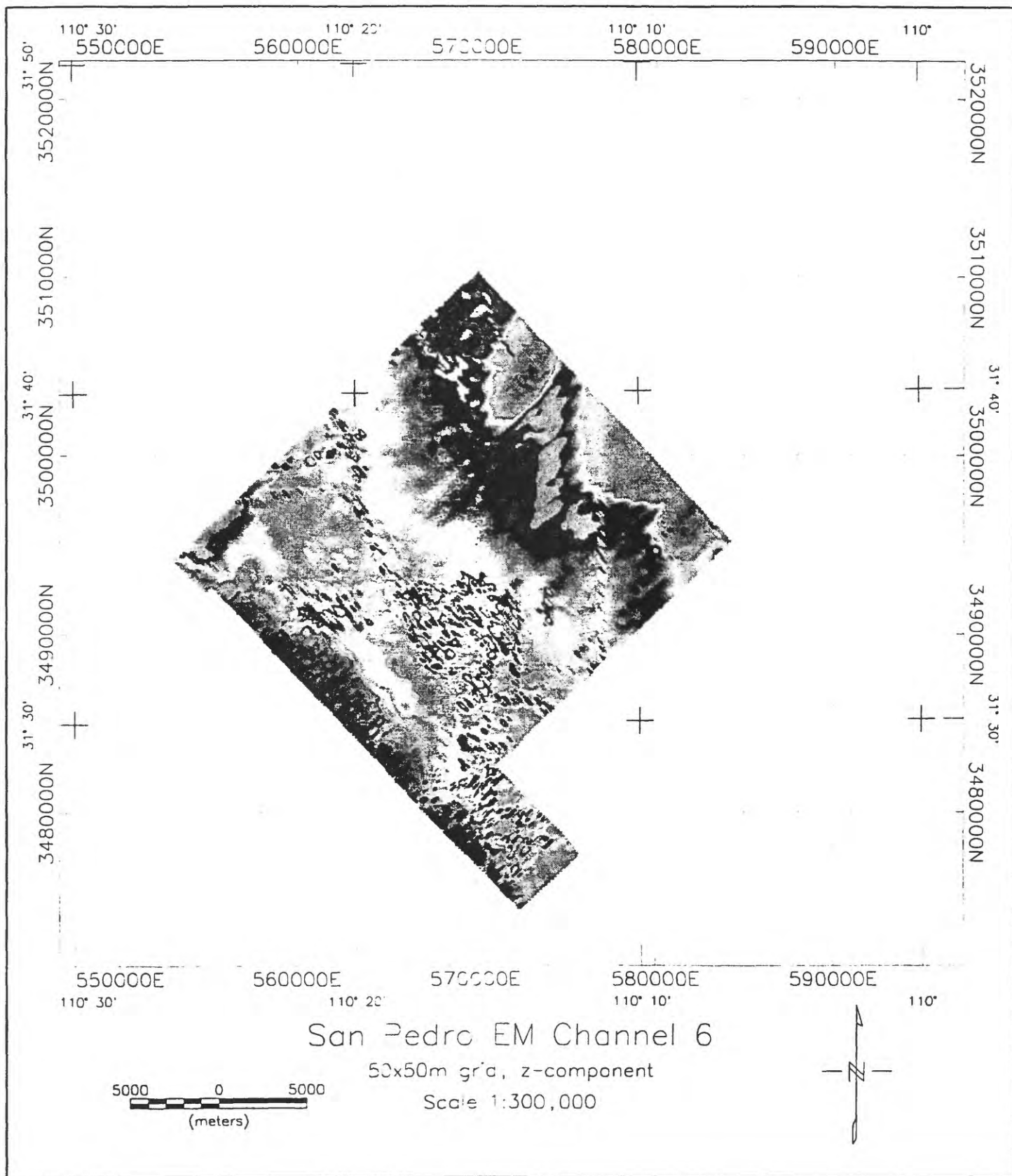


FIGURE 9.

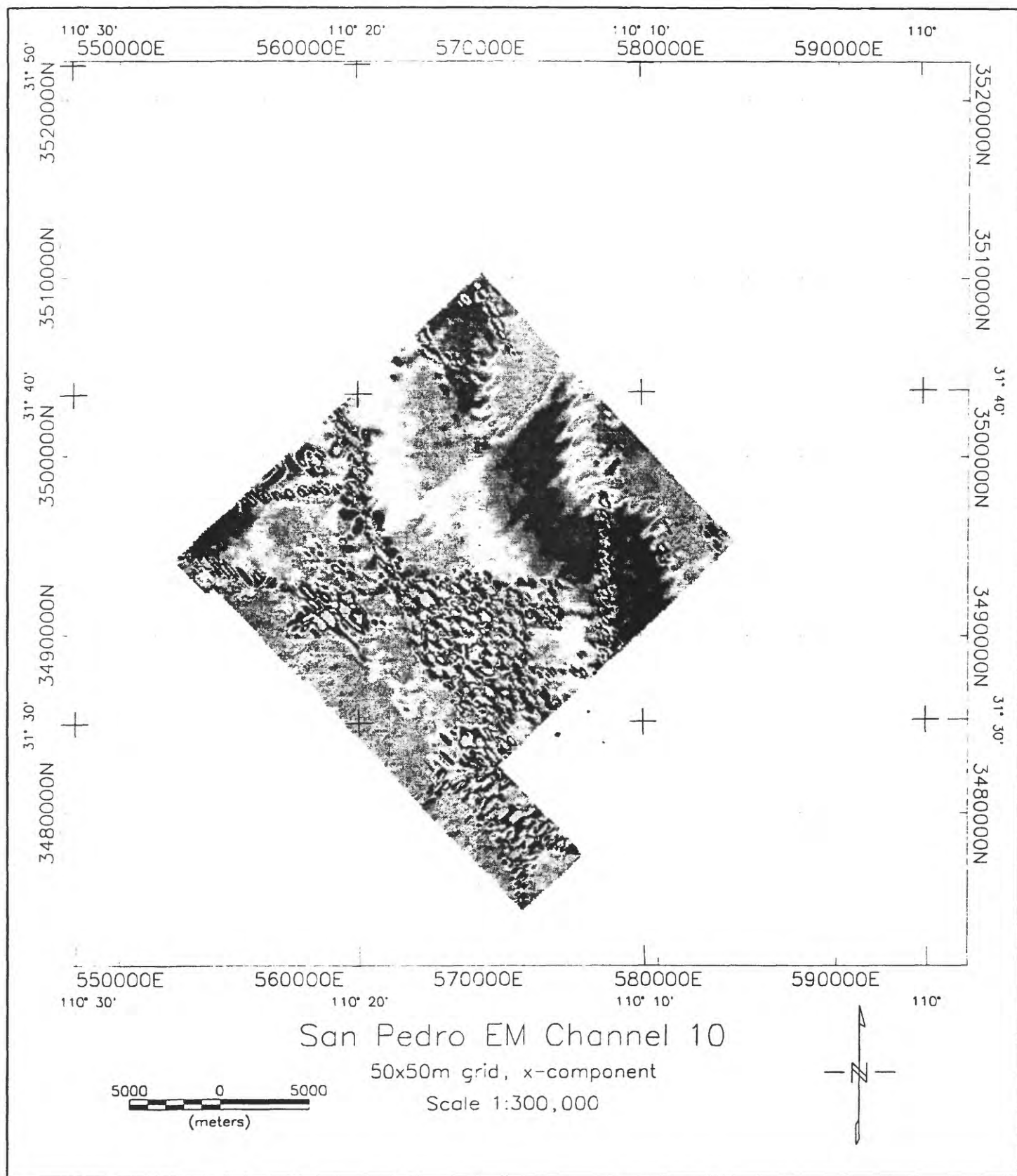
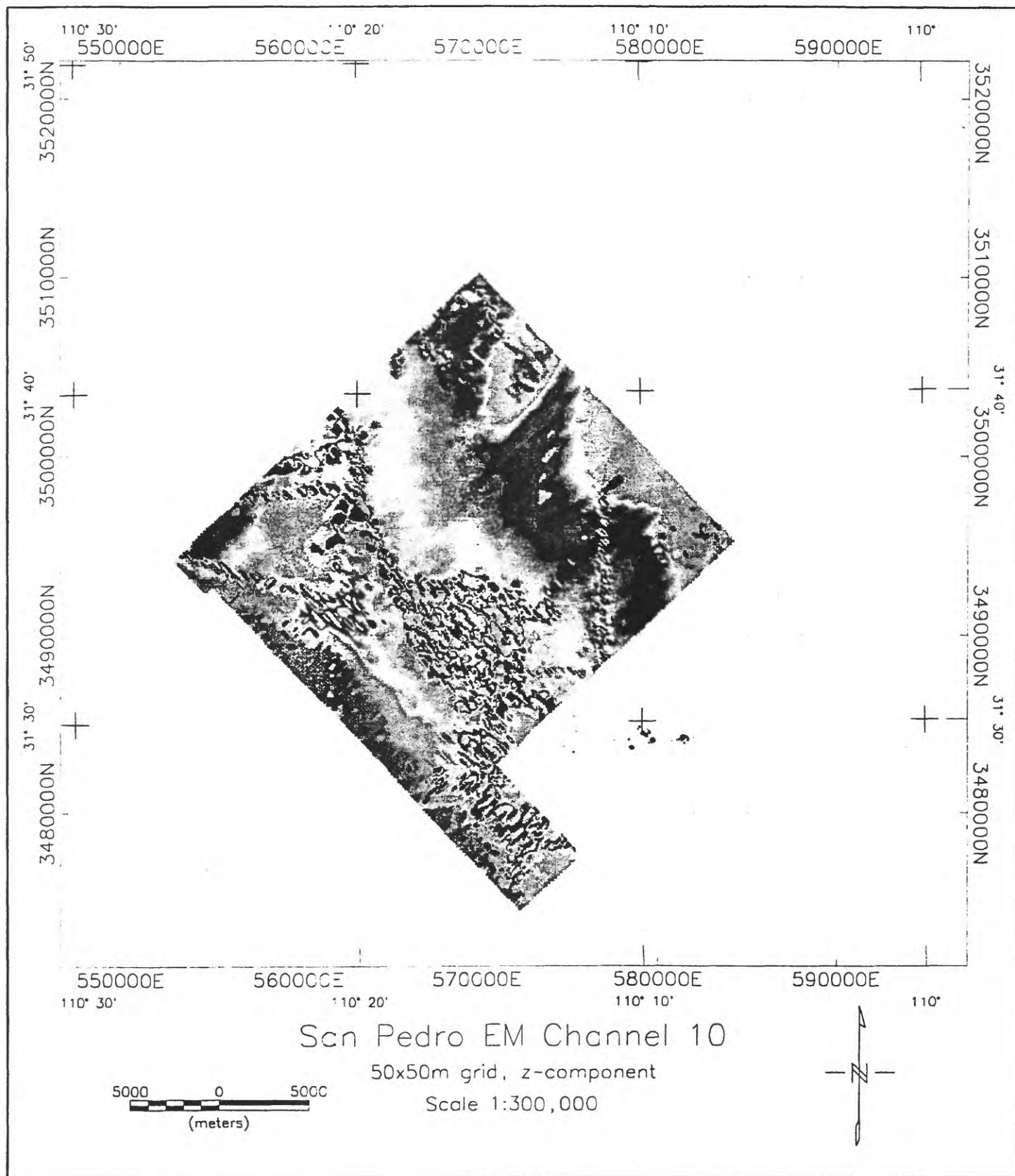
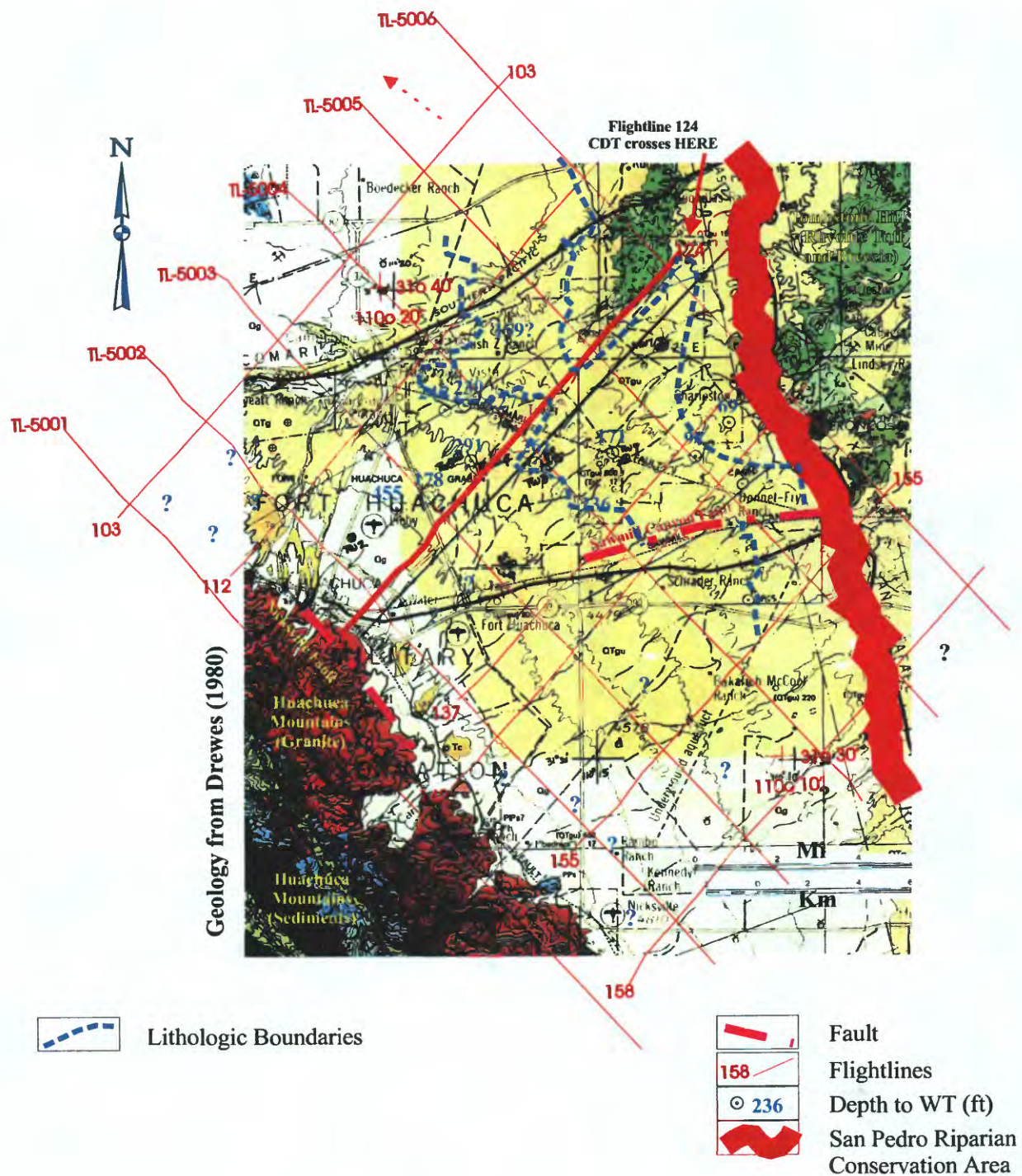


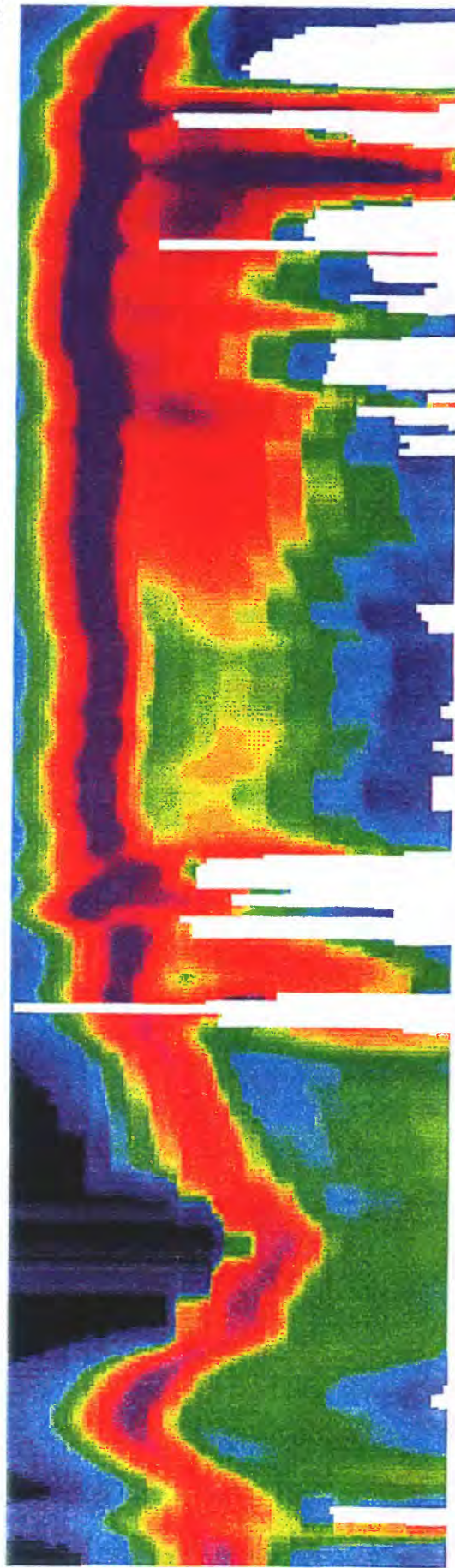
FIGURE 10.





SW

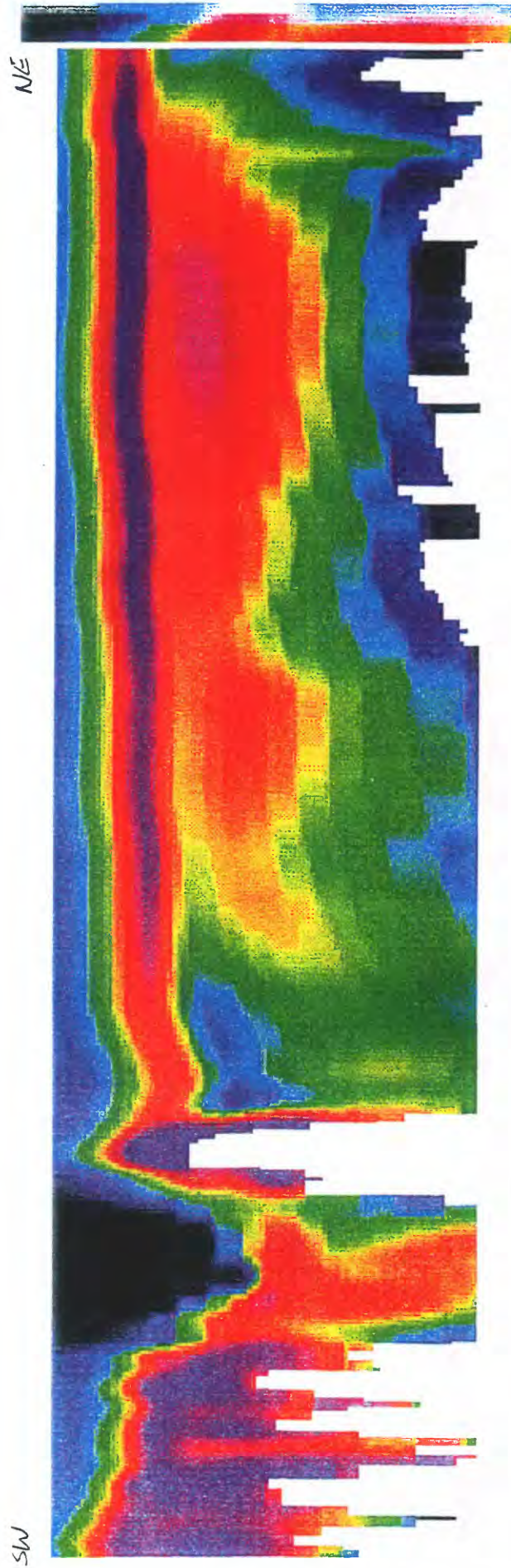
NE



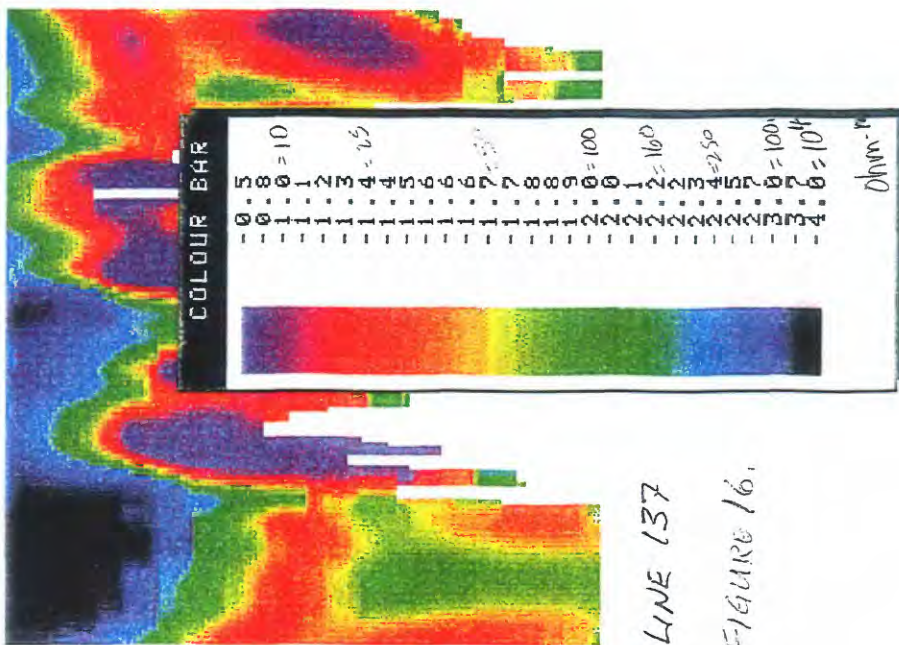
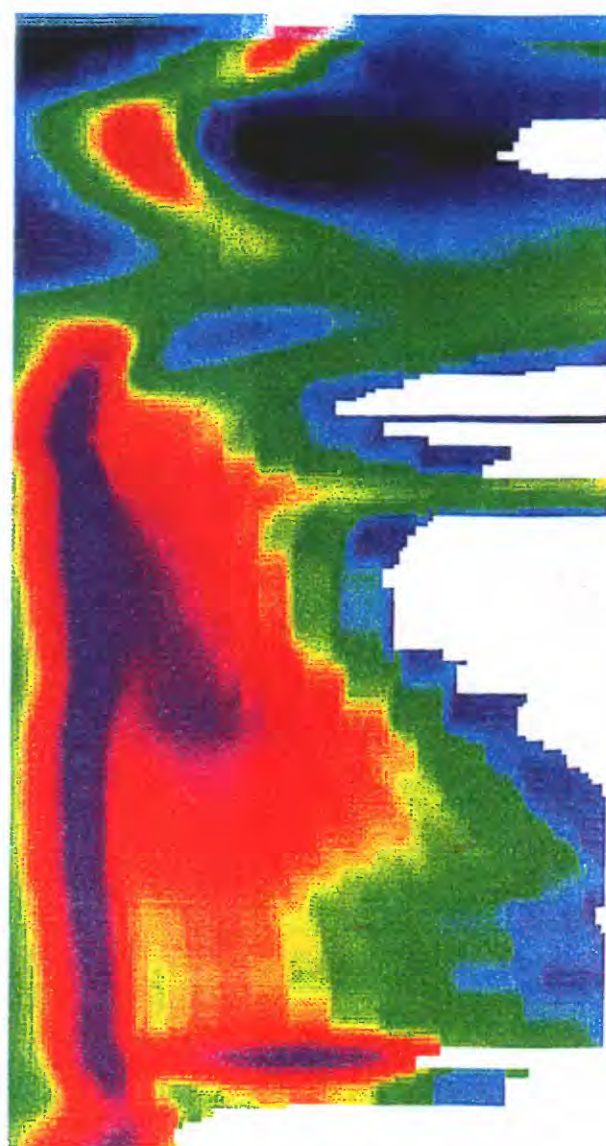
DEPTH 400m

LINE 112

FIGURE 14.



LINE 124
Figure 15.



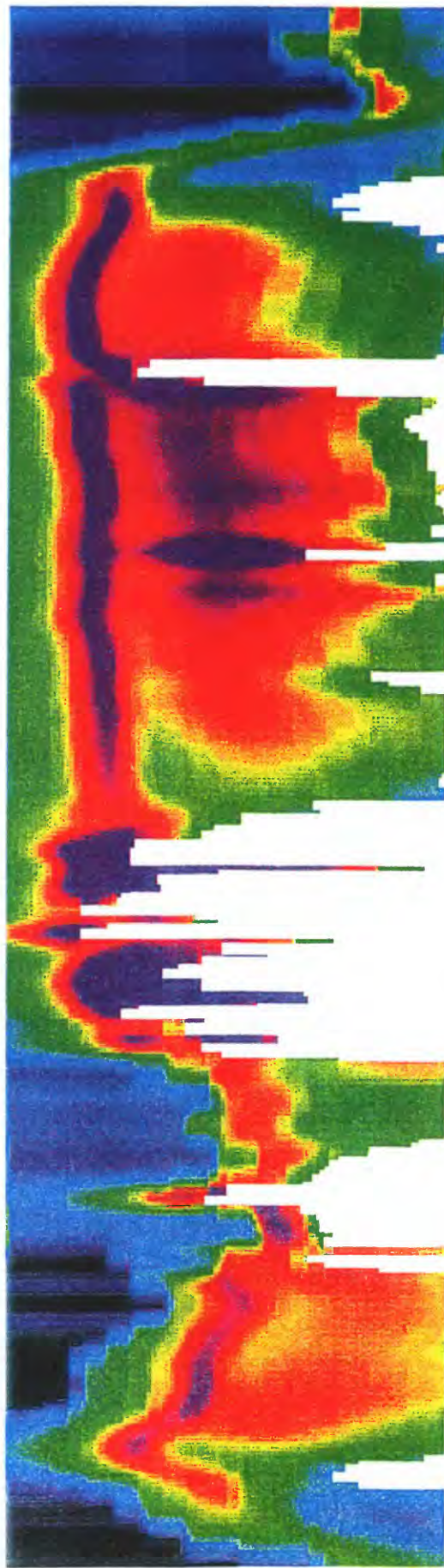
LINE 137

FIGURE 16.

DEPTH 400 m

NE

SW

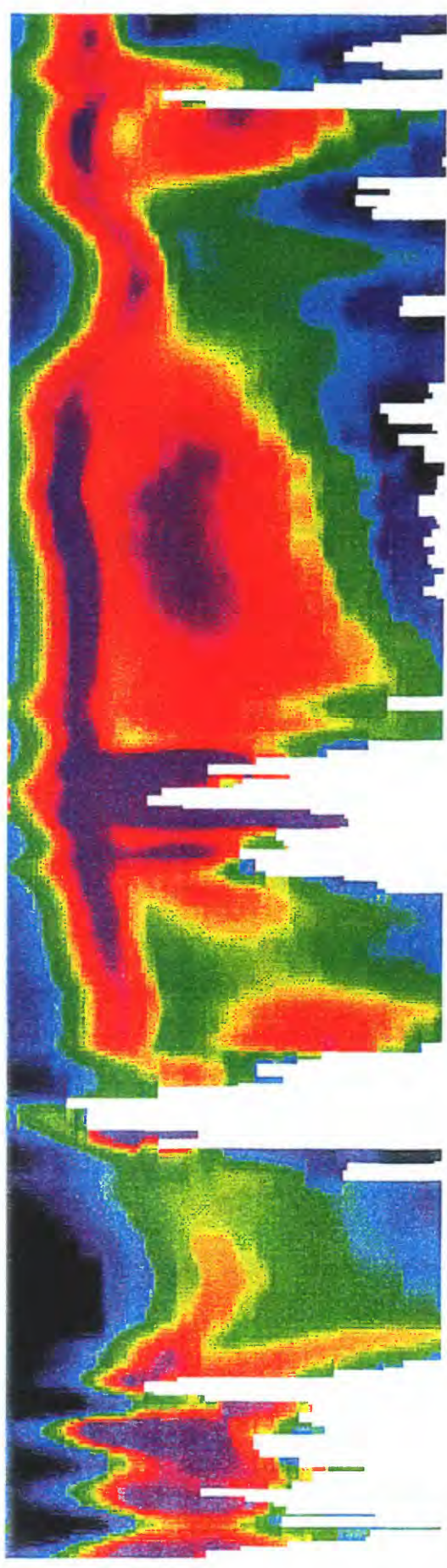


LINE 142

Figure 12

NE

SW



DEPTH 400m

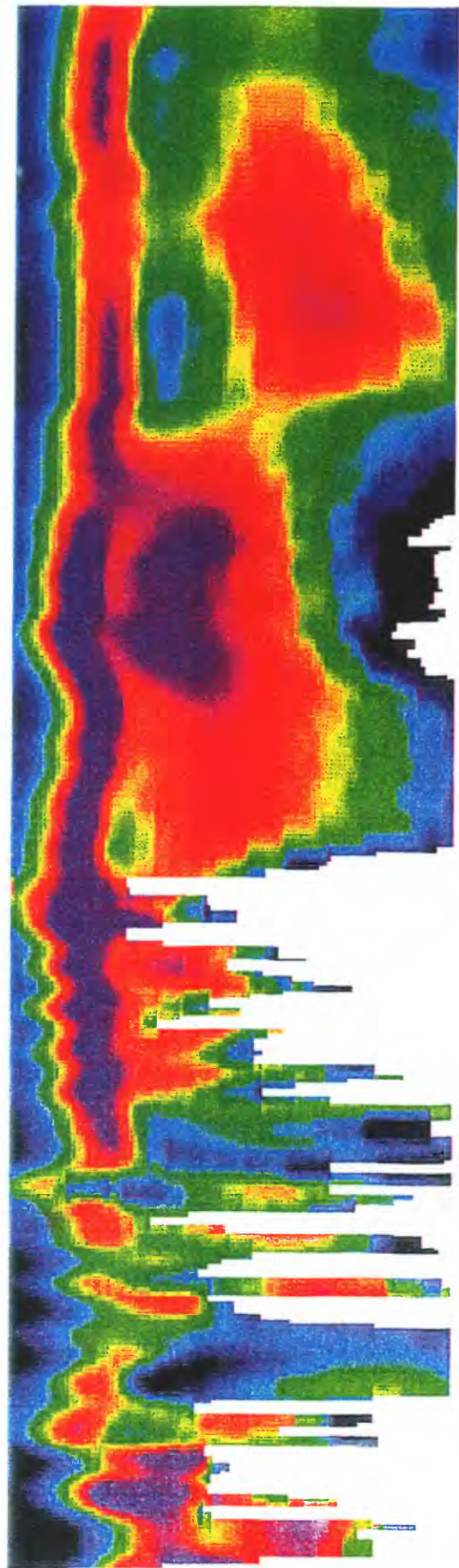
LINE 155
551 3N17

Figure 18

DEPTH 400m

NE

SW



LINE 158

Figure 13.

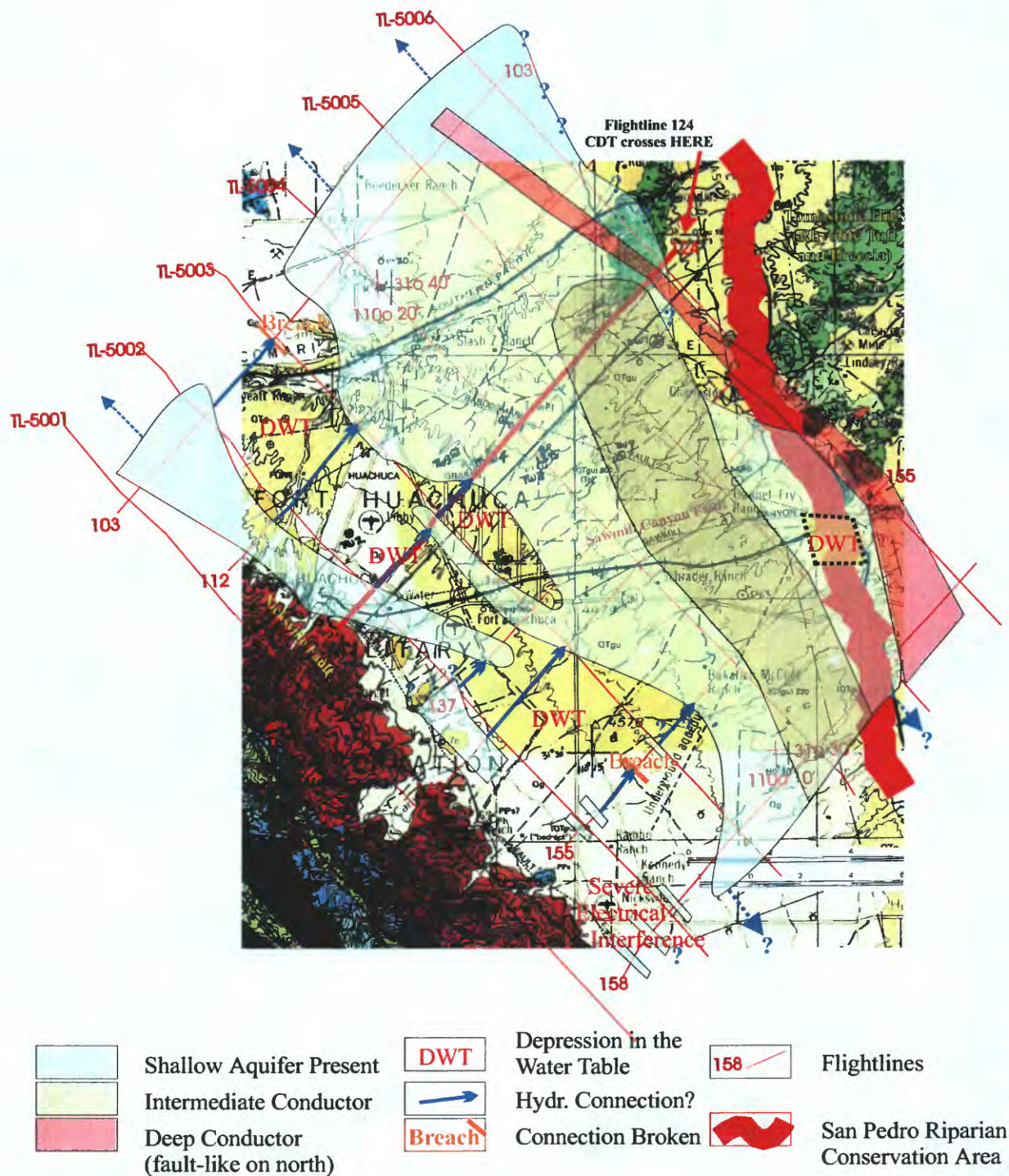


FIG. 20

